INTERNATIONAL DESIGN CONFERENCE - DESIGN 2014
Dubrovnik - Croatia, May 19 - 22, 2014.

WEIGHT OPTIMIZATION WITH A MECHATRONIC DESIGN CATALOGUE

T. Luedeke, S. Scheid and M. Vielhaber

Keywords: weight optimization, mechatronic concepts, design catalogue, knowledge

1. Introduction

Lightweight design in general is considered as one of the solutions for a responsible and sustainable handling of natural resources during the manufacturing, assembling and usage of products. In contrast to this economization strategy, growing safety requirements, power enhancement and rising customer demands regarding comfort and entertainment often result in an increase of product weight. The realization of these aspects is often based on mechatronic products. One such example is the passenger car as a mechatronic product: the increasing percentage of mechatronics is contrary to the idea of weight reduction and savings in fuel and energy. But a precise consideration of the topic shows that there are some innovative answers to reduce the weight of the overall system "car" by the application of mechatronic components and systems, e.g. drive-by-wire, smart structures or adaptronic systems. But the weight optimization is not in focus during the current development of mechatronic products which are the trigger for innovative solutions. Lightweight strategies are often employed sporadically and individually after the product development without giving any respect to the whole system. It is aimed to integrate the weight optimization task continuously into the design process provided that the functionality and the performance of the product are fulfilled and the cost target is achieved. Thus, it is very important to shift lightweight aspects into earlier design phases because there it is possible to take the highest influence on later product properties. Furthermore, lightweight knowledge is only implicitly accessible. It is mostly provided by lightweight design experts supporting the designers during product development.

Until today, no special collection of mechatronic concepts and their application on the one side, and no explicit knowledge storage of lightweight solutions and strategy application on the other side can be found. The approach proposed in this contribution provides an design catalogue consisting of mechatronic concepts – on different abstraction level (functional level, principal level with working structures, physical level) – which are suitable and can be applied for a system weight optimization (weight reduction and weight balancing). In this way, it can also be ensured that existing lightweight knowledge – which could be implicit or explicit – is stored. Thus, known knowledge can be shifted to earlier design phases and be used for the support of solution finding of design problems. The design catalogue presented here is a solution catalogue where solutions for rising design problems (with the goal of weight optimization and implementation by mechatronic concepts) on different abstraction levels are stored. In it, the mechatronic concepts are classified and characterized and thus can be support designers during solution finding. Hence, it will be possible to reduce development time when taking this catalogue into account because several design steps can be jumped over.

General definitions of knowledge, design catalogues and mechatronic functions are given in the first chapter. The next chapter deals with the approach of the design catalogue for mechatronic concepts adaptable for weight improvement. A little example shows the handling with the catalogue. Moreover, a short chapter at the end of this contribution shows the integration into the framework and the process model for weight-optimized mechatronic products.

2. Background

2.1 Knowledge

Knowledge is defined in the VDI guideline 5610 [VDI 2009] as "linked information, which enables to draw comparisons, to establish links and to make decision" whereas information "is structure data with relevance and purpose, which can be put into a context, categorised, calculated and corrected". When considering "knowledge" two different kinds can be differed: implicit knowledge is associated to a person, it is hardly to communicate and to formalise. In contrary to that, explicit knowledge is formalised on different levels (for example speech, writing etc.). Therefore, it is communicable and can be stored in various media. It is also called documented knowledge and thus, it is prerequisite for the application of communication and information technology for the support of knowledge management.

In engineering design and especially lightweight design, implicit knowledge consists of the working experience, the know-how and skills of lightweight designers. The expertise of this lightweight designer facilitates to implement the extreme difficult requirements in a lightweight design problem [Klein 2011]. Explicit lightweight knowledge is stored in lightweight design strategies (e.g. conceptual, material or structural lightweight design) and lightweight design rules (for example high moment of inertia of area or supporting effect by curvature) which are written down in databases or on paper.

2.2 Design Catalogues

Design catalogues constitute a valuable source of knowledge and information for engineers engaged in design activities. They are systematically built as tables with classifying criteria and specific rules and consist of four parts which are the structuring part, the main part, the access part as well as remarks and appendices [Roth 1994]. These tables enable precise access to contents which are solutions for design problems (functions and function structure, working principles, principle structure …). Design catalogues have an advantage over other information and knowledge sources in that way that they provide collections of known and proved solutions for design problems on different abstraction levels. Design catalogues consist according to the designer's needs of physical effects, working principles, principle solutions and embodiments like machine or standard parts, material properties or purchased components. Moreover, design catalogues should provide a quicker, more problem-oriented access to the collected data and solutions, a range of possible solutions, a greatest possible range of interdisciplinary applications and data for conventional design procedures as well as for computer-aided methods [Pahl et al. 2007].

Roth differentiates object, operation and solution catalogues [Roth 1994]. An object catalogue consists of necessary fundamental issues for designing. They are especially of a physical, geometric, technological and material nature. The VDI guideline 2222 (sheet 2) [VDI 1982] considers these catalogues as a "class of methods". Knowledge necessary for the designer is saved, but cannot be specifically assigned to certain products or functions. Examples for object catalogues are centres of gravity, volumes of geometric bodies or delivery form of sectional steel. Operation catalogues contain operations or sequences of operations which are on interest to methodical designing or engineering with regard to their application conditions and criteria for use. Rules for creation of function structures and for engineering of physical solution variants or procedures for numerical calculation of differential equations are exemplary parts of such operations catalogues. Solution catalogues represent design catalogues which are matching solutions to a certain function or task. It has to be stated that this "class of functions" can never be complete. Only in these catalogues, there is direct link between design tasks and catalogue contents. In general, design catalogues are developed as three-dimensional system from different angles [VDI 1982]: kind of catalogue (solution, object or operation catalogue), design phases, degree of complexity and abstraction. Figure 1 shows the "System of Design Catalogues" [VDI 1982].

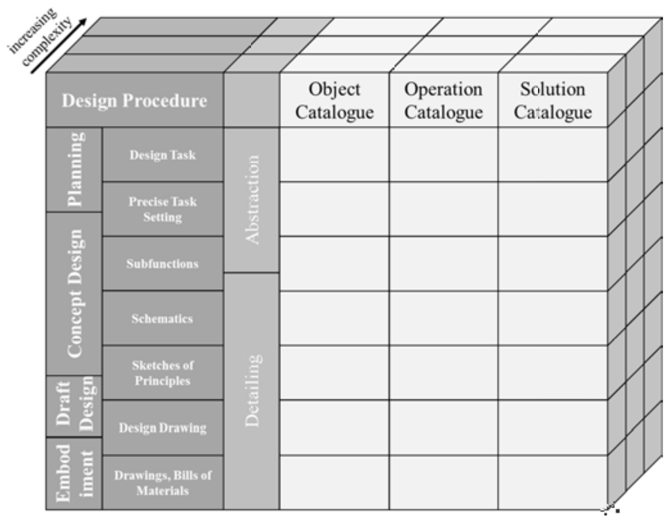

Figure 1. System of Design Catalogues based on VDI 2222 [VDI 1982]

The structure of design catalogues is determined by the four main points mentioned above (structuring part, main part, access part, remarks and appendices). The structuring part with the classifying criteria reflects the level of complexity of particular solutions. For example in the conceptual design phase, functions to be fulfilled by the solutions should be selected as classifying criteria. In contrary to that, useful classifying criteria in the embodiment and detail design phase include material properties or characteristics of standard parts. The main part of the design catalogue consists of the abstract solutions. The solutions could be represented as sketches, drawings, illustrations, physical equations or descriptions. Here, the type and completeness of the information given depends on the intended application which is determined by the design problem. The access part covering the solutions characteristics are helpful for a preliminary selection and evaluation of the solutions and involve a great variety of properties. In the remarks part the origin of the data and additional comments as well as example applications could be stored [Pahl 2007].

Today with the possibilities of knowledge storage, design catalogues are not only available on paper, they are computer-based. With modern data processing technologies the efficiency of these design catalogues can be increased. The access and the handling by users is simplified so that they can browse, navigate and interact [Franke 2004].

2.3 Mechatronic Concepts and Functions

Mechatronic products can be characterized that their function is only achieved by interaction of the different components from different domains and that there is a function relocation, for example from mechanical engineering to electrical or IT engineering [Heimann 2006]. The goal is the improvement of the functionality of a technical system with a close connection of the disciplines involved. When fulfilling functions in a mechatronic way the focus lies on a function transfer and thus a partitioning in different domains, the realisation of new functions and the possibility for implementing intelligent and self-optimising systems. Furthermore, shortcomings of strictly mechanical systems can be compensated and the robustness of these systems can be increased [Möhringer 2004].

However, the problems when considering multiple different domains bring an immense increase of complexity of functions and their solutions. This complexity often results in a cost increase. With these aspects in mind, the use of mechatronic concepts and components has always to be justified with an improvement of value and benefit [VDI 2004].

2.4 Framework for the Design of Weight-Optimized Mechatronic Products

The methodology "Design of Weight-Optimized Mechatronic Products" has been introduced by the authors to consider a continuous integration of weight properties into product development [Luedeke 2013b]. It can be understood as an integration of two different disciplines, mechatronic and lightweight design, into one development process. The methodology can be seen more than only an

integration of “Design for X” criteria. It needs a rethink in designing including the integration of X-criteria during the whole development process, not only in specific phases. Thus, every development process with an explicit focus (e.g. lowest weight, lowest cost, highest performance, …) requires a special proceeding during the design.
Mechatronics itself is an interdisciplinary and synergetic interaction of the three domains mechanical engineering, electric engineering and IT/control engineering. Thus, there are two development goals existing: on the one side the achievement of the functionality by using mechatronic concepts and on the other side obtaining the lowest weight and best weight distribution as possible.

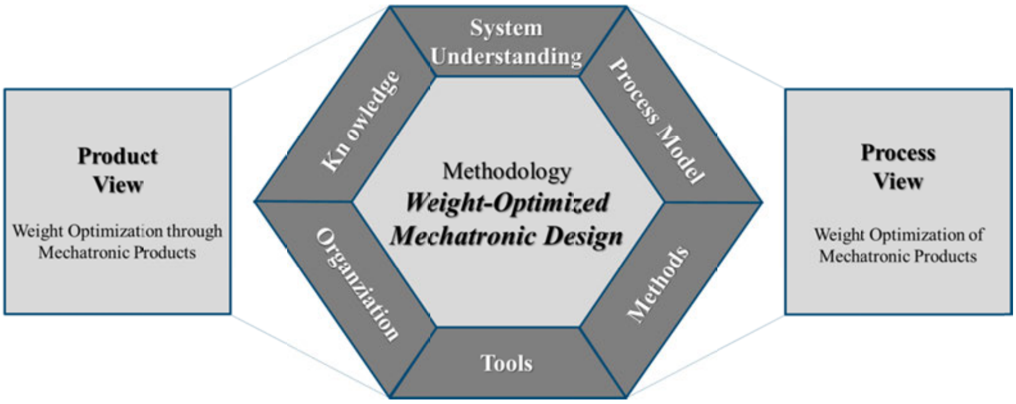

Figure 2. Framework for the Development of Weight-Optimized Mechatronic Products

The framework of the methodology (cf. Figure 2) consists of six elements – process model, methods, system understanding, tools, organization as well as knowledge – which are the basis of the methodology adressing two different perspectives, the product view and the process view. The product view – the weight optimization by application of mechatronic products – needs an analysis of given mechatronic concepts in terms of their ability or of their potential for a weight reduction or an improved weight distribution. The process view – the weight optimization of mechatronic products – offers a procedure for the development of weight-optimized mechatronic products following some aspects of the VDI guideline 2206 [VDI 2004].
In this contribution, the product view – represented by a design catalogue – is focused.

3. Approach for a Design Catalogue

Based on requirements for a knowledge storage of mechatronic concepts and lightweight solutions the benefit and the general structure of the design catalogue are presented. An example for accessing the design catalogue for the design problem “weight optimization with mechatronic concepts” is given at the end of the chapter.

3.1 Requirements for Knowledge Storage of Lightweight Design

Besides the general consideration of knowledge storage during product development additional requirements for the storage of lightweight design knowledge can be set (partially from [Schmidt 2004]):

- Support for the determination of the lightweight potential and benefit
- Assistance for executing the strategies for new or renewed designs
- Integration of important calculation and simulation tools
- Finding of novel solutions and their application
- Tools for decision for lightweight design principle or structure
- Integration of lightweight design elements as features

3.2 Requirements for Knowledge Storage of Mechatronic Concepts

Additionally, the requirements for knowledge storage for mechatronic concepts which are of high complexity and an involvement of different domains can hardly be found. It has to be understood that

an unification identical to the lightweight design is difficult to reach. Most of the parameters are product-specific (e.g. introduced forces, area of operation etc.). Moreover, further system components (e.g. control units, suppliers) must be in consideration. It is often necessary to ensure system safety with the application of independent redundancies (mostly mechanically realized) which are needed when a system failure is occurring.
The most important aspect for knowledge storing of mechatronic concepts is the comparison with predecessor concepts and the benefits resulting from the application of these new concepts. Saving potentials (here especially weight improvement and optimizations) or cost and function benefits have to be documented in order to select and choose the suitable mechatronic concept.
Furthermore, it seems very important to accumulate explicit knowledge especially for mechatronic solution sets (for example x-by-wire applications, adaptronics, etc.). Thus, general characteristics of the different solutions in one solution set can be provided (e.g. common interfaces).

3.3 Benefit of the Design Catalogue

The design catalogue presented here shows several benefits:

- Transfer and synthesis of implicit knowledge of lightweight design experts to explicit and easily accessible knowledge
- Description and access of novel lightweight design principles
- Classifying and characterisation of mechatronic concepts suitable for weight optimization
- Provision of novel lightweight solutions – more than the traditional lightweight design solutions – in all abstraction levels (functional, principal and physical level) which are supported and managed with mechatronic concepts
- Evaluation of trade-offs (e.g. cost, performance, functionality, safety, …) and choice of weight-optimizing mechatronic concepts
- Shifting of solution finding activities to earlier phases, increasing of knowledge and shortening of design time (cf. Figure 3: with the application of known solutions accessible in the design catalogue the knowledge necessary for designing is growing faster and shifted to earlier design stages)

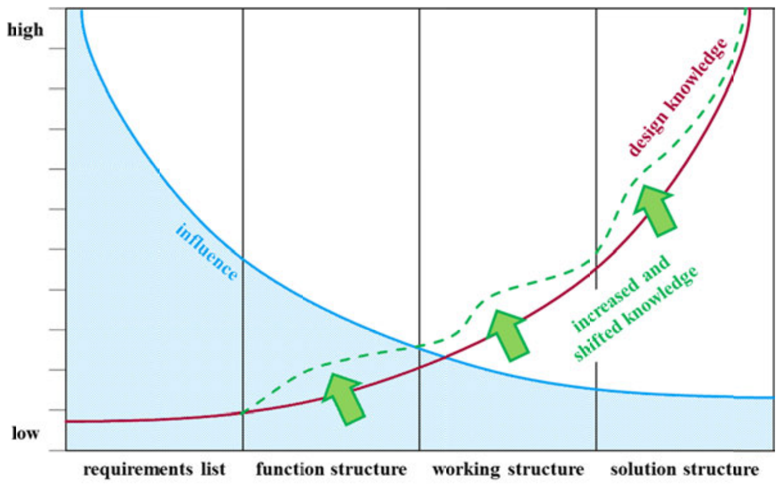

Figure 3. Design Paradox (similar to [Ehrlenspiel 2009])

3.4 General Structure

The design catalogue first proposed in [Luedeke 2013a] is a solution catalogue according to [Roth 1994]. The catalogue presented here is a further development of this first approach. Additionally, to the solutions only on physical level first approaches to solutions in the functional and principal level are considered. Furthermore, the integration of the catalogue into the general design process is regarded for the first time.

Based on the design task – fulfilling or improving specific functions by using mechatronic concepts with the potential for weight improvement – there is a stepwise refinement in this catalogue for finding the solution(s). Because this design catalogue is only an approach for structuring and collecting mechatronic concepts suitable for weight optimizations, it has to be stated that there is no claim of completeness for the mechatronic solutions.
The catalogue is structured in that way described above (see also Figure 4). It consists of the structuring part where classifying criteria are the type of design (new or renewed design) and the abstraction level of design problem (functional, principal, physical level). This structuring part has the task of a consistent subdivision of the catalogue content [Roth 1994].
Based on this classification, the main part and the access part are derived. The main part provides the general solutions which are divided in the type of implementation of the weight optimization (for example substitution or addition of a mechatronic system), the location of the weight optimization (improved component or surrounding components). In the access part, the solution set based on mechatronic concepts and functions and thus the explicit solutions and their application are characterised. In the remarks additionally to necessary interfaces supporting details can be deemed, for example supplies for power or trade-offs like cost, functionality or performance. These trade-offs and the weight improvement value provided by a certain solution could be of high importance when implementing lightweight design principles and using mechatronic concepts.

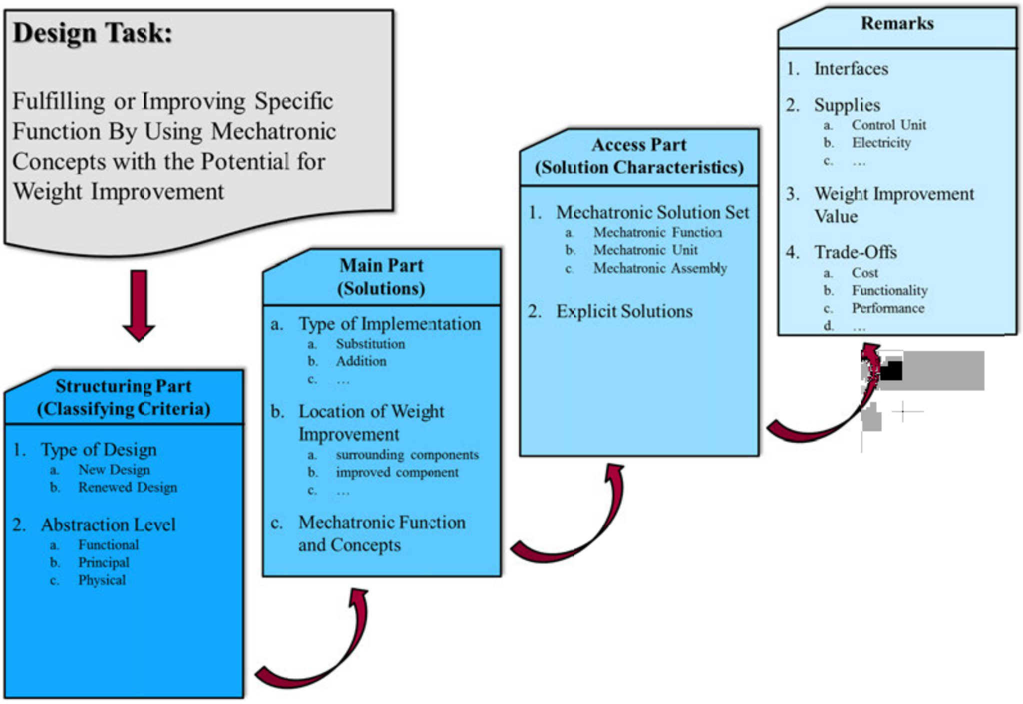

Figure 4. General Procedure of Use of the proposed Design Catalogue

The selection and choice of the mechatronic solutions is mainly covered by the review and the comparison of the aspects given in the remarks part of the design catalogue. Important and essential roles play in this case the trade-offs which are rising when mechatronic and lightweight solutions are applied. It is often advisable to execute a cost-benefit-analysis or a functionality-benefit analysis for choosing the right solutions. Moreover, the integration potential of the mechatronic solution found in the catalogue to the supervisory system with the aid of the given interfaces should be in consideration.

3.5 Example

As example for the use of the design catalogue should serve the application of shape memory alloys in technical products. The alloys in her function as actuator substitute engines and gears for the execution of linear or rotatory motions. Certain shape memory alloys as a solution from the solution set adaptronics could actuate a load with a multiple of their own weight (often a hundred or thousand times). The specific example given here is the application of shape memory alloy in a clamping system for a fuel tank cap in an automobile instead of electrical actuators. The substitution gains a weight optimization of more than 90 % in the fuel tank cap system [Langbein 2011]. However, the suppliers and the interfaces of the shape memory alloy have to be adapted to the existing surrounding system.

Table 1 shows the solution finding procedure within the design catalogue.

1. Structuring Part
    a. Type of Design: renewed design
    b. Abstraction Level: physical level
2. Main Part
    a. Type of Implementation Substitution of a component/subsystem
    b. Location of Weight Improvement: component/subsystem itself
    c. Mechatronic Function: function integration of two mechanical functions (clamping and moving)
3. Access Part
    a. Mechatronic Solution Set: Adaptronics
    b. Explicit Solutions: Shape Memory Alloy
    c. Solution Description: titanium-nickel alloy
4. Remarks
    a. Value of Weight Improvement: up to 90%
    b. Trade-Offs: cost, new interfaces
    c. Supplies: additional energy supply

Table 1. Example of Design Catalogue Use

Structuring Part (Classifying Criteria)		Main Part (Solutions)			Access Part (Solution Characteristics)			Remarks		
Type of Design	Abstraction Level	Type of Implementation	Location of Weight Improvement	Mechatronic Function and Concepts	Mechatronic Solution Set	Explicit Solution	Solution Description	Value of Weight Improvement	Trade-Offs	Supplies
Renewed Design	Functional	Substitution	Component	function integration (clamping & moving)	Adaptronics	Shape Memory Alloy	TiNi alloy	up to 90%	Cost	Energy Supply
			Surrounding Components	...	...	...		...	...	...
			...	...	...	...		...	...	...
		Addition	...	...	...	...		...	...	...
		...	...	...	...	...		...	...	...
	Principal	...	...	...	...	...		...	...	...
	Physical	...	...	...	...	...		...	...	...
New Design	Functional	...	...	...	...	...		...	...	...
	Principal	...	...	...	...	...		...	...	...
	Physical	...	...	...	...	...		...	...	...

4. Integration to Design Process

4.1 General Design Procedure

The process model (Figure 5) shows a holistic management of weight properties throughout the whole development process starting with the task setting and requirements and finishing with the real product. The approach for managing and monitoring is to introduce analysis gates both between and within the main design process steps product planning and task setting, conceptual design as well as embodiment and detail design.

The stage of conceptual design serves as a first estimation and rough calculation of the weight properties as well as an overview for crosslinks and interdependencies within the system and subsystems which can result in further weight propagation. After substantiation the system concept in an important analysis gate, the final layout and design of the system and its subsystems is performed in the detail and embodiment design stage which ends with another analysis gate providing a very detailed value of the future weight properties.
Moreover, the different design stages are developed in sense of mechatronic design. Thus, the known process model for mechatronic design (V model) as well as the stages system design, domain-specific design and system integration are reflected within the different steps of conceptual and detail design. It has to be stated that the V models in the stages are similar to the 3-level process model of [Bender 2006]. It is divided into different levels: system level, subsystem level and component level. For more detail about the model, see [Luedeke 2013b].

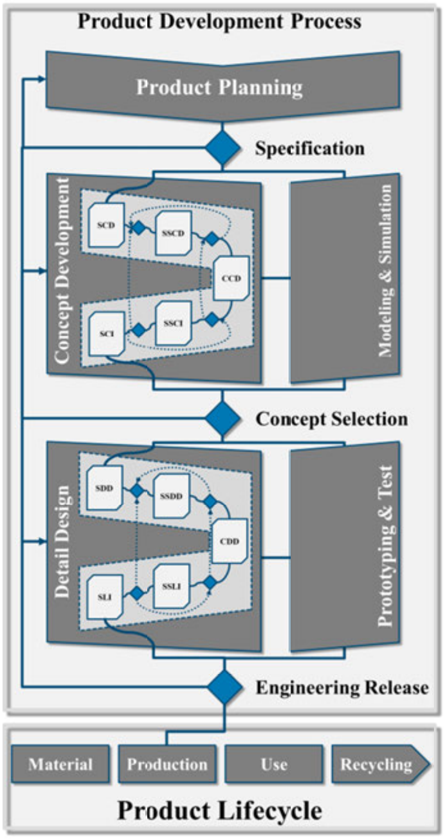

Figure 5. Process Model [Luedeke 2013b]

4.2 Integration into the Design Process

The integration of design catalogues into a general design process can happen in all design phases beginning with requirements collection to embodiment design [Roth 1994, 2001]. The catalogues primarily serve to support the synthesis steps in the design process while known partial solutions for design problems are aggregated to an overall solution. Hence, the application and use of design catalogues affects the development time in that way that certain design steps – responsible for solutions finding – can be skipped over and thus the time can be reduced.
When integrating the design catalogue with mechatronic concepts for weight reduction to the process model the different system and abstraction level must be considered. On the one side, a known mechatronic system could serve as solution for a subsystem required after system decomposition (subsystem level, physical abstraction level). On the other side, a known mechatronic function could replace several functions realized in a mechatronic, mechanical or electrical way (component level, functional abstraction level). Thus, a reduction of the development time is reached whenever the

design catalogue is in use because of the skipping of design steps – especially for solution finding tasks. This skipping can occur from analysis to synthesis stage, from analysis to later analysis steps or from synthesis to later synthesis steps.
However, the interfaces caused by the mechatronic solutions selected have to be proved and eventually adapted for fitting to the overall solution. That means whenever a mechatronic solution from the design catalogue is chosen the properties induced by this mechatronic concepts have to assured. Provisions or clues for these interfaces or other adjustments are given in the remarks part within the design catalogue.
An example for taking mechatronic solutions from the design catalogue and applying them in the design process is given in Figure 6.

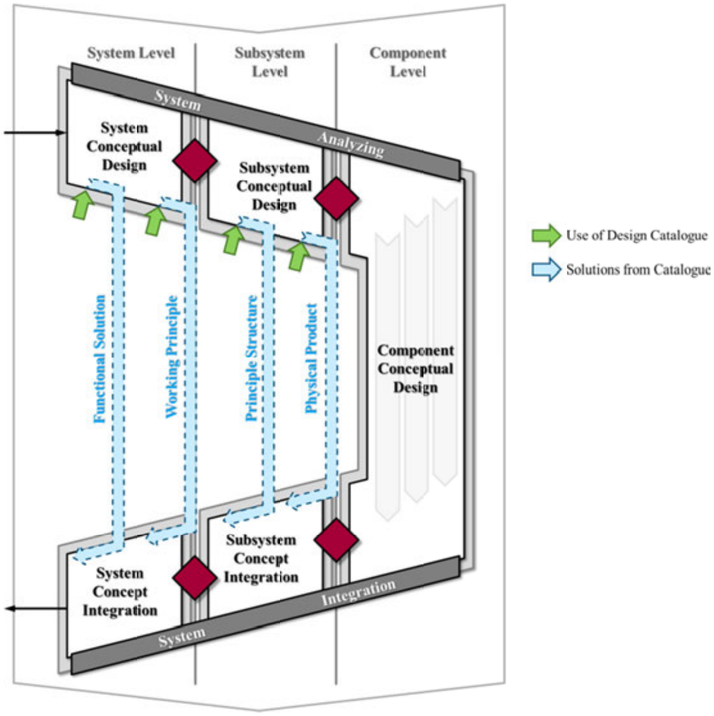

Figure 6. Examples for Application of the Design Catalogue in the Design Process (here: Concept Design Stage)

Thus, with the application of the design catalogue presented a mechatronic solution for a function in the system conceptual design shows for example that this function and its solution is considered again in the integration of the subsystems concepts to the system concept. It behaves in exactly the same way with the application of the design catalogue in the other situations (finding a solution for a working principle, for a principle structure or for a physical subsystem).
This example shows that the design catalogue can be used in many situations in the design process for weight optimized products.

5. Conclusion and Outlook

In this contribution, it is shown that the usage of design catalogues simplifies the design process in that way that known solution principles can be adapted to the design problem and be integrated into the design procedure. Hence, the time for designing can be reduced – some design steps can be jumped over – and the knowledge during the procedure is faster accessible. Moreover, the knowledge generation or status about the systems is shifted to earlier design phases. In the design catalogue presented here, mechatronic concepts are stored which are suitable for the optimization of weight and weight balance in a product. These mechatronic concepts are classified and categorized and can be applied in different abstraction levels (functional, principal and physical level). Thus, the designers are given an explicit knowledge storage for the first time where they can choose mechatronic concepts with lightweight potential.

Further research will be done on the handling of trade-offs to weight improvement (for example design and product costs, product performance and behaviour etc.). This as a basis serves for multi-criteria decision-making which is subject when considering lightweight design and weight improvement.

References

Bender, K., "Embedded Systems – Qualitätsorientierte Entwicklung", Springer, Berlin, 2005.

Ehrlenspiel, K., "Integrierte Produktentwicklung – Denkabläufe, Methodeneinsatz, Zusammenarbeit", Hanser, München, 2009.

Franke, H. J., Löffler, S., Deimel, M., "Increasing the Efficiency of Design Catalogues by Using Modern Data Processing Technologies", Proceedings of the 8th International Design Conference – DESIGN 2004, D. Marjanovic (ed.), FMENA, Zagreb, 2004, pp. 853-858.

Heimann, B., Gerth, W., Popp, K., "Mechatronik: Komponenten – Methoden – Beispiele", Hanser, München, 2006.

Klein, B., "Leichtbau-Konstruktion – Berechnungsgrundlagen und Gestaltung", Vieweg & Teubner, Wiesbaden, 2011.

Langbein, S., Czechowicz, A., "Die Form denkt mit", MECHATRONIK, no. 11-12, 2011, pp. 44-47.

Lopez Garibay, J. A., Binz, H., "Design Catalogues as Knowledge Management and Educational Tools in Microsystem Engineering Design", Proceedings of the 15th International Conference on Engineering Design – ICED 2005, A. Samuel, W. Lewis (eds.), Melbourne, 2005, Paper ID: DS35_56.49

Lopez Garibay, J. A., Binz, H., "Design Catalogues for Microsystem", Proceedings of the 9th International Design Conference – DESIGN 2006, D. Marjanovic (ed.), FMENA, Zagreb, 2006, pp. 913-920.

Luedeke, T., Scheid, S., Vielhaber, M., "Mechatronische Konzepte zur Gewichtsreduzierung und -verteilung", Proceedings of VDI-Fachtagung Mechatronik 2013, T. Bertram, B. Corves, K. Janschek (eds.), Aachen, 2013a, pp. 129-134.

Luedeke, T., Vielhaber, M., "Early Development of Weight-Optimized Mechatronic Products", Proceedings of the 23rd CIRP Design Conference – Smart Product Engineering, Abramovici, M., Stark, R. (eds.), Bochum, 2013b, pp. 695-704.

Möhringer, S., "Entwicklungsmethodik für mechatronische Systeme", HNI-Verlagsschriftenreihe Band 156, Gausemeier, J. (ed.), Heinz-Nixdorf-Institut, Paderborn, 2005.

Pahl, G., Beitz, W., Fedhusen, J., Grote, K.-H., Wallace, K., Blessing, L., "Engineering Design – A Systematic Approach", Springer, London, 2007.

Roth, K., "Konstruieren mit Konstruktionskatalogen – Band 1: Konstruktionslehre", Springer, Berlin, 2000.

Roth, K., "Konstruieren mit Konstruktionskatalogen – Band 2: Konstruktionskataloge", Springer, Berlin, 1994.

Schmidt, W., "Methodische Entwicklung innovativer Leichtbau-Produkte", Fortschritt-Berichte VDI Nr. 369, VDI-Verlag, Düsseldorf, 2004.

Verein Deutscher Ingenieure, VDI guideline 2206, "Design Methodology for Mechatronic Systems", Beuth, Berlin, 2004.

Verein Deutscher Ingenieure, VDI guideline 2222 – sheet 2, "Design Engineering Methods – Setting Up and Use of Design Catalogues", Beuth, Berlin, 1982.

Verein Deutscher Ingenieure, VDI guideline 5610, "Knowledge Management for Engineering – Fundamentals, Concepts, Approach", Beuth, Berlin, 2009.

Wiedemann, J., "Leichtbau – Elemente und Konstruktion", Springer, Berlin, 2006.

Dipl.-Ing. Tobias Luedeke, Research Associate
Saarland University
Department of Mechatronics
Institute of Engineering Design
Campus E 2.9, R. 1.07
66123 Saarbruecken, Germany
Telephone: +49 681 302 71234
Email: luedeke@lkt.uni-saarland.de
URL: http://www.lkt.uni-saarland.de